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A new link between plant metabolism and circadian rhythms?

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The rotation of the Earth around its axis generates 24 h cycles of environmental change, such as daily rhythms of light and temperature. Circadian clocks, cellular biological oscillators that generate 24-hour rhythms of gene expression and metabolism, are thought to synchronize the functioning of organisms with these daily environmental changes. Circadian regulation enables organisms to anticipate environmental changes such as dawn and dusk, and co-ordinate their metabolism, physiology and behaviour with daily changes in the environment. This is particularly important for plants, which cannot move to escape environmental challenges.

In the experimental model *Arabidopsis thaliana* (Arabidopsis), correct circadian regulation increases photosynthesis, biomass accumulation, survival, seed number and viability (Green *et al.*, 2002; Dodd *et al.*, 2005). It is estimated that almost 90% of Arabidopsis transcripts can oscillate in abundance over the 24 h cycle, with about 30% of transcripts being circadian-regulated (Michael *et al.*, 2008). This multitude of genes under circadian control highlights the pervasiveness of circadian regulation in co-ordinating the functioning of plants with their rhythmic environment. Because photosynthetic light harvesting can only occur during the day, and stored carbohydrate reserves require mobilization at night to supply respiration and growth, plant metabolism is intimately associated with cycles of day and

night. Building upon extensive underpinning research into the molecular genetics of circadian oscillators, the interactions between metabolism, signalling and circadian regulation have become an important growth area in plant circadian biology. For example, breakthroughs have demonstrated that the rate of nocturnal starch breakdown is intricately timed so that plants do not starve at night (Graf *et al.*, 2010), sugars produced by photosynthesis can entrain the circadian clock (Haydon *et al.*, 2013), and the concentrations of ions such as Ca^{2+} and Mg^{2+} are regulated by, and can regulate, the circadian oscillator (Dodd *et al.*, 2007; Feeney *et al.*, 2016).

In this issue of *Plant, Cell and Environment*, Shin *et al.*, 2017 identified another potential connection between metabolism and circadian regulation. The authors established that an energy-sensing protein complex can influence circadian rhythms. AKIN10 (known also as KIN10 or SnRK1.1) is a catalytic α-subunit of Snf1 (sucrose non-fermenting1)-related kinase 1 (SnRK1), which is an evolutionarily conserved energy sensor. SnRK1 controls metabolic enzymes through protein phosphorylation (Sugden *et al.*, 1999), and also regulates > 1000 transcripts in response to starvation by controlling transcription factor activity (Baena-González *et al.*, 2007; Mair *et al.*, 2015). SnRK1 plays such a fundamental role in energy metabolism that AKIN10 knockouts are lethal (Baena-González *et al.*, 2007). By overexpressing AKIN10 with a chemically-inducible promoter, the authors explored the role of AKIN10 in circadian regulation. They found that inducing very high levels of AKIN10 expression caused the circadian clock to assume a long period, of up to 5 h longer than controls, when plants were under conditions of continuous light. Interestingly, the long circadian period caused by AKIN10 overexpression disappeared in experiments performed under continuous darkness, such that AKIN10 overexpressing plants had the same circadian period as the controls. When AKIN10 overexpressors were in constant darkness, supplementing the growth media with sugars did not restore the long circadian period that occurred in the light. The authors interpret this to indicate that starvation does not cause the insensitivity of circadian period to AKIN10 overexpression in darkness. Instead, Shin et al.

(2017) propose that the influence of AKIN10 upon circadian period forms a response to the light environment.

The study also found that under both light/dark cycles and constant light, AKIN10 overexpression caused a delay in the peak of expression of transcripts encoding the evening-expressed circadian oscillator component GIGANTEA (GI). This is interesting because *gi*-11 mutants are insensitive to a long-term effect of sucrose upon the circadian oscillator (Dalchau *et al.*, 2011). Additionally, the authors found that the period of plants harbouring the *tic*-2 mutation in the circadian oscillator gene *TIME FOR COFFEE* (*TIC*) had reduced sensitivity to the effects of AKIN10 overexpression, suggesting a role for TIC in the regulation of circadian period by AKIN10.

It is intriguing that AKIN10, a key player in the regulation of energy metabolism of Arabidopsis, can influence circadian rhythms. The work of Shin et al. (2017) builds on studies demonstrating bidirectional regulatory interactions between circadian regulation and metabolism (Fig. 1). For example, the environmental cycles of day and night dictate when photosynthesis can occur, and photosynthesis is also regulated extensively by the circadian oscillator (Dodd *et al.*, 2014). Importantly, the products of photosynthesis can, in turn, entrain the circadian oscillator (Haydon *et al.*, 2013). Each morning, the upregulation of photosynthesis causes an accumulation of sugars, which alters circadian oscillator gene expression and can adjust the circadian phase (Haydon *et al.*, 2013). Similarly, the circadian oscillator controls the rate of nocturnal starch consumption (Graf *et al.*, 2010), with one mathematical model for the regulation of nocturnal starch degradation assuming the presence of a sugar sensing mechanism (Feugier & Satake, 2013). In this way, the environment affects metabolism, metabolism regulates the circadian oscillator, and the circadian oscillator regulates metabolism (Fig. 1).

By demonstrating that a subunit of the central energy sensor SnRK1 affects the functioning of the circadian oscillator, Shin et al. (2017) have identified a mechanism that has the potential to couple metabolism with circadian regulation. This adds to the evidence that

reciprocal regulation between the circadian oscillator and energy metabolism exists across several Kingdoms of life. For example, in mammals there are circadian rhythms of NAD^+ and ATP synthesis and feeding can reset the circadian oscillator, and in both plants and cyanobacteria, the availability of energy can regulate circadian rhythms (Rust *et al.*, 2011; Bass, 2012; Haydon *et al.*, 2013). Therefore, the long circadian period caused by AKIN10 overexpression (Shin et al. 2017) could point to a role for AKIN10 in interfacing the circadian oscillator with both metabolism and environment, given the extensive influence of environmental conditions upon the metabolic state of plants. In future, it will be informative to determine the function and position of SnRK1 within the circadian system, to understand how a sensor of cellular energy status contributes to the responses of plants to the daily changes that occur in the environment.

Figure legend

Figure 1. Reciprocal regulation between the environment, metabolism and circadian rhythms in *Arabidopsis thaliana*. SnRK1 is thought to regulate metabolic enzyme activity and transcription in response to energy availability. In this issue, Shin et al. (2017) have identified a new role for the SnRK1 catalytic subunit AKIN10 in regulating circadian period (shown in red).

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